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The socio-organizational age of artificial intelligence in medicine

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Abstract

The increasing pressure on Health Care Organizations (HCOs) to ensure efficiency and cost-effectiveness, balancing quality of care and cost containment, will drive them towards a more effective management of medical knowledge derived from research findings. The relation between science and health services has until recently been too casual. The primary job of medical research has been to understand the mechanisms of disease and produce new treatments, not to worry about the effectiveness of the new treatments or their implementation. As a result many new treatments have taken years to become part of routine practice, ineffective treatments have been widely used, and medicine has been opinion rather than evidence based. This results in suboptimal care for patients. Knowledge management technology may provide effective approaches in speeding up the diffusion of innovative medical procedures whose clinical effectiveness have been proved: the most interesting one is represented by computer-based utilization of evidence-based clinical guidelines. As researchers in Artificial Intelligence in Medicine (AIM), we are committed to foster the strategic transition from opinion to evidence-based decision making. Reviews of the effectiveness of various methods of guideline dissemination show that the most predictable impact is achieved when the guideline is made accessible through computer-based and patient specific reminders that are integrated into the clinician's workflow. However, the traditional single doctor–patient relationship is being replaced by one in which the patient is managed by a team of health care professionals, each specializing in one aspect of care. Such shared care depends critically on the ability to share patient-specific information and medical knowledge easily among them. Strategically there is a need to take a more clinical process view of health care delivery and to identify the appropriate organizational and information infrastructures to support this process. Thus, the great challenge for AIM researchers is to exploit the astonishing capabilities of new technologies to disseminate their tools to benefit HCOs by assuring the conditions of knowledge management and organizational learning at the fullest extent possible. To achieve such a strategic goal, a guideline can be viewed as a model of the care process. It must be combined with an organization model of the specific HCO to build patient careflow management systems. Artificial intelligence can be extensively used to design innovative tools to support all the development stages of those systems. However, exploiting the

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knowledge represented in a guideline to build them requires to extend today's workflow technology by solving some challenging problems.

Keywords: Health care organization; Knowledge management; Learning organization; Evidence-based medicine; Clinical guideline; Patient care process

1. Introduction

The increasing pressure on health care organizations (HCOs) to ensure efficiency and cost-effectiveness, balancing quality of care and cost containment, will drive them towards a more effective management of medical knowledge derived from research findings. There is a general appreciation that clinical decisions must be based on evidence to a much greater degree than they have been in the past. They should be made by combining three factors; *evidence*, *values*, and *resources*. However, many health care decisions are still based principally on values and pay little attention to evidence derived from research, the *scientific factor*, and to resources, the *socio-economic factor*. This will change: as the pressure on those factors increases, decisions will have to be made and justified explicitly and publicly.

There are unacceptable delays in the implementation of many findings of research [5]. This results in suboptimal care for patients. Collections of systematic reviews and critical appraisals of primary research are valued knowledge sources [6]. However, their proliferation is creating its own information explosion. Knowledge management technology may provide effective approaches in speeding up the diffusion of innovative medical procedures whose clinical effectiveness have been proved: the most interesting one is represented by computer-based utilization of evidence-based clinical guidelines [1–4,7]. As researchers in artificial intelligence in medicine (AIM), we are committed to foster the strategic transition from opinion-based to evidence-based decision making.

As defined by the Institute of Medicine, clinical guidelines are ''systematically developed statements to assist practitioner and patient decisions about appropriate health care for specific clinical circumstances'' [8]. Clinicians, policy makers, and payers see guidelines as a tool to reduce variability in practice, control costs, and improve patient care outcomes.

However, the development of good guidelines does not ensure their use in practice. Therefore, to maximize the likelihood of a clinical guideline being used we need coherent dissemination and implementation strategies to capitalize on known positive factors and to deal with obstacles to implementation that have already been identified [9]. Reviews of the effectiveness of various methods of guideline dissemination show that the most predictable impact is achieved when the guideline is made accessible through computer-based and patient specific reminders that are integrated into the clinician's workflow.

A further dimension of the problem of guideline dissemination in HCOs needs to be considered. For its understanding we must start from the fact that the single doctor–patient relationship is being replaced by one in which the patient is managed by a team of health care professionals, each specializing in one aspect of care. Such shared care depends critically on the ability to share patient-specific information and medical knowledge easily among care providers. Indeed it is the present inability to share guidelines across systems and organizations that represents one of the major impediments to progress towards an evidence-based care. Strategically there is a need to take a more clinical process view of health care delivery and to identify the appropriate organizational and information infrastructures to support this process.

To achieve such a strategic goal, a guideline can be viewed as a model of the care process. It must be combined with an organization model of the specific HCO to build a patient careflow management system (CfMS). Artificial intelligence (AI) can be extensively used to design innovative tools to support all the development stages of a CfMS. However, exploiting the knowledge represented in a guideline to build a CfMS requires that we extend today's workflow technology by solving some challenging problems. In contrast with most industrial or office processes, medical processes may often be unpredictable, because of the intrinsic uncertainty and complexity present in most of the patient management phases. As a matter of fact, even if a guideline illustrates the steps to follow in pre-defined situations, it may happen either that a new, unpredictable situation arises, or the physician, that is the final decision-maker, is not always compliant with the guideline. Thus, a CfMS must be flexible enough to handle sudden modifications of the pre-defined plan, and to truly support health care professionals in their work rather than overly constrain them.

Another peculiarity of HCOs is that medical professionals are not normally situated in front of a computer. The latter is a more typical situation for administrative office operators. Thus, a CfMS relying on simple message delivery among workstations is not suitable. It is essential to find modalities for sending messages able to reach the operators as soon as possible, but with particular attention not to burden them excessively. That is to say that the system must have knowledge about the urgency of the tasks, according to the patient condition, in order to choose the best modality for advising the operator. Mobile and wireless network technology promises great possibilities in this respect.

2. Knowledge-based health care organizations

Knowledge has come to be recognized and handled as a valuable entity in itself. It has been called *the ultimate intangible*. There are some estimates that intellectual capital now comprises typically 75–80% of the total balance sheet of companies. *Today, knowledge is a key enterprise asset* [10]. This is particularly true in HCOs where the typical business is knowledge-based since they are composed largely by specialists who direct and discipline their own performance through organized feedback from patients, colleagues, and managers. Each medical specialty has its own knowledge and there is a head who is a specialist managing a team whose work is done as required by an individual patient's diagnosis and condition. Because the actors are specialists, they should do their work according to the best medical knowledge and the head of the team should focus the actors' skill and knowledge on the clinical outcome of the patient care process.

A knowledge-based organization is one that manages the three strategic information and knowledge processes of *sense making*, *knowledge creation* and *decision making* into a continuous cycle that Choo [11] calls the "knowing cycle" (see Fig. 1). Starting at the top

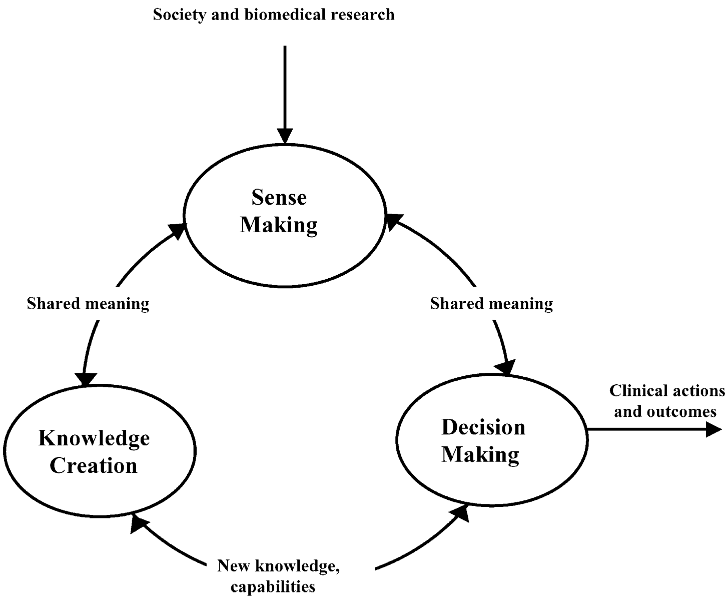

Fig. 1. The organizational learning cycle.

of the diagram, streams of information from the society (citizen health needs, national or international health policies, available resources, etc.) and medical research (new findings and technologies) are continuously acquired, analyzed, and connected together to develop shared meanings of what is happening outside and inside the HCO in order to plan and make decisions. Shared interpretations are needed to define the organization's intent or vision about what new knowledge and capabilities the organization needs to develop.

If sense making reduces equivocality sufficiently and reveals that the situation facing the organization is a familiar one which the organization has learned to deal with before, then the organization can make a decision by selecting a pattern of action among those already known. However, if sense making indicates that the organization lacks some knowledge or capability to respond properly to the situation, a knowledge creation process is activated. The results of sense making allow the recognition of knowledge gaps and the identification of the initial criteria to evaluate the usefulness or value of new knowledge that is being created.

Having developed understanding and knowledge, the organization has to act. Choosing patient care management plans requires coping with substantial equivocality and uncertainty. Sense making retains some vagueness in its interpretation to allow for future flexibility. Knowledge creation produces new capabilities that are still untested, and innovations whose effects on improving quality of care, clinical effectiveness, cost containment may be hard to predict. Through its decision making, an organization reduces risks, uncertainty, and complexity by specifying the kinds of patient information to be acquired, the medical tasks to be executed, the resources to be used, and the criteria to evaluate decision options. The output of decision making is therefore the selection of a pattern of actions that moves the organization closer to its goals, but that is also an attempt by the organization to adapt to a changing environment as perceived through its sense-making activity.

This paper focuses on the possible contributions by the AIM community to the design and development of innovative tools which may facilitate the management of clinical practice knowledge in HCOs.

3. Knowledge creation

In the area of knowledge management, it has been pointed out that a large part of knowledge is not explicit but tacit. Following Polanyi's [12] epistemological investigation, tacit knowledge is characterized by the fact that it is personal, context specific, and therefore hard to formalize and communicate. Explicit, on the other hand, is the knowledge that is transmittable through any systematic language. Polanyi contends that human beings acquire knowledge by actively creating and organizing their own experiences. Thus, explicit knowledge represents only the tip of the iceberg of the entire body of knowledge. As he puts it, "we can know more than we can tell". Tacit knowledge influences information needs perceived by care providers, as well as the course of care processes, but further epistemological analysis needs to be developed in order to establish which part of tacit knowledge can be articulated and, then, explicitly represented [13].

Nonaka and Takeuchi [14] investigated the interaction between tacit and explicit knowledge concluding that they are not totally separate but mutually complementary entities. They interact with each other in the creative activities of human beings. Their dynamic model of knowledge creation is anchored to a critical assumption that human knowledge is created and expanded through *social interaction* between tacit and explicit knowledge. This process has been called *knowledge conversion*. Knowledge conversion is a social process between individuals and not confined within an individual. Four different modes of knowledge conversion have been postulated (see Fig. 2): *socialization*, *externalization*, *combination*, and *internalization*.

1. *Socialization* is the process of sharing experiences that creates tacit knowledge as shared mental models and technical skills. Apprentices learn their physical and cognitive skills through socialization by observing, assisting, and imitating the behaviors of experienced practitioners. Socialization thus transfers tacit knowledge through the medium of shared experience.
2. *Externalization* is the process of conversion of tacit into explicit knowledge through the development of models, protocols or guidelines.
3. *Combination* is the process of recombining or reconfiguring bodies of existing explicit knowledge that leads to the creation of new explicit knowledge.
4. *Internalization* is the process of learning by repetitively doing a task applying the explicit knowledge so that the achieved outcomes become absorbed as new tacit knowledge of the individual.

Socialization and internalization are both aspects of apprenticeship. The former concerns the socio-organizational implementation of apprenticeship while the latter concerns

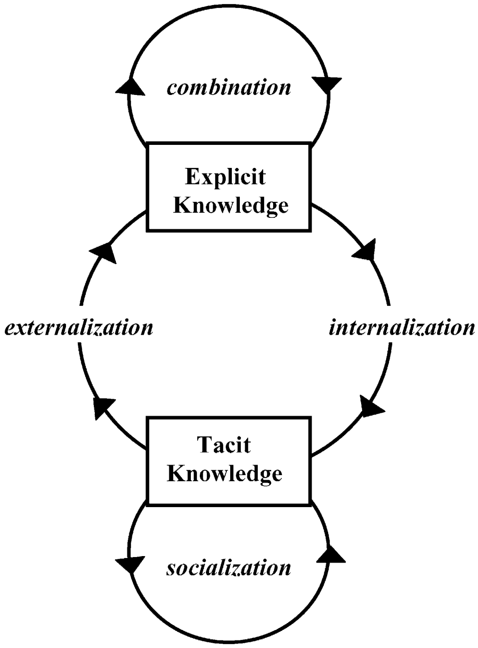

Fig. 2. The knowledge conversion processes in a knowledge creating organization.

cognitive aspects. Also externalization and combination are both phases of a reification process. Representing tacit knowledge as explicit allows for reusability of objects while composing explicit knowledge chunks allows for building more complex objects. Thus, the knowledge creation process can be restructured into two sub-processes: acquiring knowledge through apprenticeship and making knowledge reusable.

Knowledge management aims to properly facilitate and stimulate these knowledge conversion processes. The ultimate goal is that of converting as much tacit knowledge into explicit knowledge as possible and combining bodies of explicit knowledge coming from different sources. Such processes are strategic for HCOs, where the dissemination of new clinical knowledge is essential for the continuous improvement of medical care. Explicit knowledge is, in fact, inherently more capable of diffusing than tacit knowledge.

Thus, knowledge management can be defined as a framework and a tool set for improving an organization's knowledge infrastructure [15], aiming at "getting the right knowledge to the right people in the right form at the right time at the right cost". Evidently, knowledge management is not a one-shot activity. It must be daily supported within an organization through the most appropriate information and communication technology (ICT).

Although the literature on knowledge management has expanded impressively in recent years, there is a need for a greater clarity and understanding of the nature and the economics of the variegated forms of biomedical, in general, and clinical, in particular, knowledge. Nelson and Winter [16] acknowledge that the separation between tacit and explicit knowledge is not inherent in the knowledge. They write:

> The same knowledge, apparently, is more tacit for some people than for others. Incentives, too, clearly matter: when circumstances place a great premium on effective articulation, remarkable things can sometimes be accomplished.

Explicit knowledge serves as a knowledge depository, as a reference point, and possibly as an authority. But this knowledge can only perform those functions when people are able to interpret the adopted knowledge representation and to use that knowledge in practice. It means that what is explicit for one person or group may be tacit for another. Thus, the context — temporal, spatial, cultural and social — becomes an important consideration in any discussion about explicit medical knowledge.

The process that is needed to harness medical knowledge to health care practice has been analyzed by Haynes and Haines [17]. Biomedical researchers disseminate their results through peer reviewed journals, but the small number of clinically important studies are spread amongst a large number of publications. New specialized journals have begun to appear which report critical appraisals of results supposed to be ready for use in clinical practice. A practice guideline developed by a recognized health authority may provide a useful representation of a clinical policy which individual practitioners may decide to adopt. However, guidelines must be tailored to local and individual circumstances and this process requires the cooperative efforts of expert clinicians and managers to create such knowledge [18]. However, such knowledge is not usually explicitly represented in generic guidelines.

Since AIM researchers develop tools to support knowledge-based activities, we need to better understand the kinds of knowledge used in them. Some authors [19,20] suggest considering knowledge attributes which are meant to be useful in analyzing where knowledge transactions or activities take place, rather than where knowledge of different types may be said to reside. At least three attributes of knowledge need to be considered: *extent of representation*, *extent of multi-organizational diffusion* and *extent of use in a specific organization*. Each attribute can be represented by a binary variable for the sake of simplicity although in real human activities they are obviously continuous. We consider two main types of knowledge-based activities in medicine: the creation of "research knowledge" and the creation of "clinical knowledge". The former activity produces clinical findings, either published or still unpublished, and field trials, either under development or already published. This knowledge can be considered tacit from the viewpoint of clinicians. On the other hand, clinical knowledge can be considered as the typical example of explicit knowledge, particularly when available as a guideline.

Both tacit and explicit knowledge may be either diffused or undiffused across HCOs, as well as either manifest or latent within a specific HCO. Given the three binary knowledge attributes, eight types of knowledge have been identified, as shown in Fig. 3. Such a classification does not pretend to be general since it needs to be adapted according to the knowledge, experience and skills available within the HCO. Thus, it can be viewed as a proposal for identifying the types of knowledge involved in the activities of a HCO.

Diffused knowledge is knowledge whose value has been assessed by a more or less large community. This may motivate other HCOs or health care professionals to evaluate

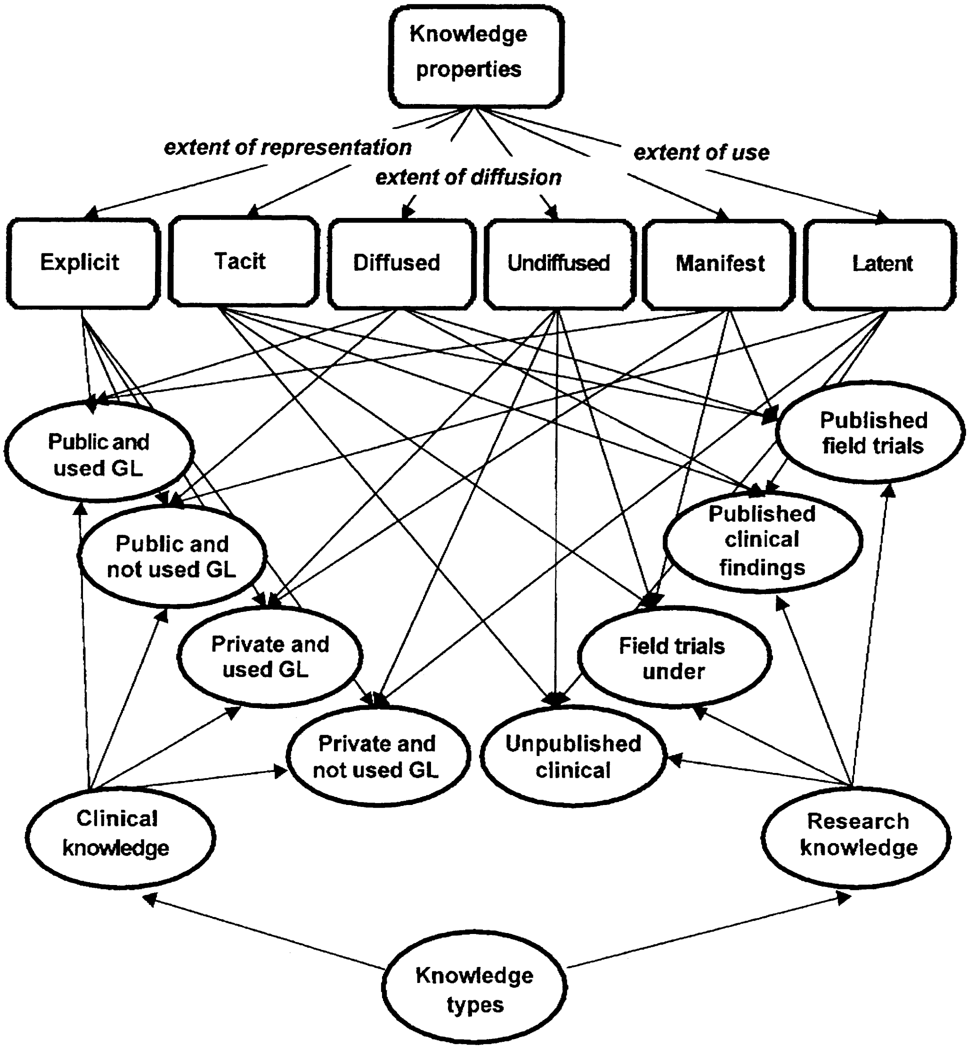

Fig. 3. The knowledge types in a knowledge creating HCO.

carefully the opportunity to acquire it. When it is also explicit and manifest such an action can be both faster and more economic.

Manifest knowledge is knowledge that is referred to by "an individual or team" during their daily work, which is to say in a specific "socio-temporal context" [20]. The knowledge is latent if it is not invoked explicitly in the typical course of activities. Again, the concept of a context is important. In this case two possible sub-cases can be considered.

1. A *knowledge source exists*, but it is out of sight, so it can be considered as a *displaced* knowledge source. For example, it is represented by a guideline which can be either

public (diffused among some HCOs) or private (undiffused but manifest within another HCO). This observation is crucial in understanding the economic problem raised by the management of knowledge in various situations: when the knowledge source is displaced, new needs for knowledge representation can be fulfilled at a rather low cost; whereas, when there is no knowledge source, the representation costs can be very high: they include the development of the necessary knowledge models and their implementation using suitable representation languages.

2. A *knowledge source does not exist*, but it would be possible to produce one. For example, it exists either as a published paper or a report describing the results of a field trial executed for assessing the effectiveness of an innovative clinical procedure. A further binary splitting can be considered, based on the existence or non existence of enough clinical evidence. Where there are uncertainties due to the early stage of those clinical studies and no knowledge source is available to resolve uncertainties, then it is possible that some clinical authority exists whom the clinical team can use for dispute resolution.

The map of knowledge types proposed here can be used by a HCO to plan efforts and estimate costs for creating the new knowledge needed to properly manage innovative clinical procedures. Knowledge management tools must be developed and used to speed up such complex socio-organizational process.

4. Decision making

Decisions are commitments by individuals or organizations to actions which are justified in relation to goals and objectives, and are predicated on information and beliefs about how the selected strategies and the actions selected will lead to desired outcomes. At least two important models of decision making process need to be considered: the rational model and the process model. The rational model, developed initially by Simon [21], conceptualizes decision making as goal directed and problem driven, and choice behavior as regulated by purposely designed processes, so that the organization acts in a manner that is intentionally and procedurally rational. However, the information and knowledge requirements of a purely rational mode of decision making are always daunting in clinical practice. We cannot assume to have complete and reliable information about the patient's clinical state and the effects of alternative clinical decisions, nor we cannot afford the time and cost of acquiring this complete knowledge. Whichever the alternative, making a decision always creates both intended and unintended consequences, and the unanticipated consequences may well turn out to be highly significant. We rarely have a well-defined or completely consistent set of preferences, both patient and organizational preferences, or criteria by which we can, for example, rank the alternatives in order to choose the most desirable one. Simon suggests instead that humans are only "boundedly rational" so that while they attempt to be rational, their behavior is limited by their cognitive capabilities and by constraints that are part of the organization.

As a consequence of bounded rationality, the organizational decision maker behaves in two distinct ways when making decisions. First, she/he should look for a course of action that is satisfactory enough, i.e. evidence-based in clinical practice, rather than seeking for the optimal solution. Second, organizations and organizational actors simplify the decision process following protocols or guidelines whose clinical effectiveness has been proved. Thus, an essential way to bridge the gap between organizational rationality and the individual's bounded rationality in a HCO is to develop knowledge management systems which facilitate the diffusion of evidence-based best practices.

A process model, exemplified by the work of Mintzberger et al. [22] elucidates the phases and cycles that give structure to apparently complex and dynamic decision making activities. It may require HCOs to reorganize themselves on the basis of effective and efficient care process models.

Both the rational and the process model assume that organizational goals are sufficiently unambiguous, while they are different in terms of *technical uncertainty* about how goals are to be achieved: it can be judged lower in the former than in the latter. When technical uncertainty is high, decision making tends to be a dynamic process marked by frequent changes and unexpected interruptions and exceptions. Implementing a clinical practice guideline in a real environment initially requires its adaptation to the specific organization, that is designing and testing the care process. Once such a process attains the desired outcomes, a rational model better describes the behaviors of individual decision makers.

5. Learning organizations

Although learning is something undertaken and developed by individuals, organizations can foster or inhibit the process. The organizational culture within which individuals work shapes their engagement with the learning process. Organizations that position learning as a core characteristic have been termed "learning organizations" and this concept is a fundamental one in the context of organization development. It is important to note the difference between the terms *learning organization* and *organizational learning*. In discussing learning organizations, we are focusing on the *what*, and describing the systems, principles, and characteristics of organizations that learn and produce as a collective entity. Organizational learning, on the other hand, refers to *how* organizational learning occurs, i.e. the skills and processes of creating new knowledge by doing.

Can a hospital, a general practice, or a health care authority be said to learn? They are not simply a collection of individuals: they are composed of multiple interacting teams, each with highly specialized knowledge, skills, and technologies. The execution of important tasks requires these diverse communities to bridge their differences and integrate their knowledge and skills to create a new, shared perspective [23], that is to create knowledge according to Nonaka and Takeuchi [14]. Such considerations may suggest that we should think of organizational learning in terms of the "organizational environments" within which individuals think and act. Organizations have been conceived as behavioral settings for human interaction, fields for the exercise of power, systems of institutionalized incentives that govern individual behavior, or socio-cultural contexts in which individuals interact. But such an approach still leaves us with the problem of linking individuals to organizational processes. By establishing rule-governed ways of deciding, delegating and setting the boundary of membership, a collectivity becomes an organization capable of acting. As Chester Barnard [24] points out, organizations are systems in which individuals collaborate to perform tasks that arise repetitively (such as diagnosing and treating patients in a HCO). Every collaborative system embodies a strategy for dividing up the tasks it regularly performs and delegating the components to individual members, thereby establishing organizational roles. The organization's "task system", its pattern of interconnected roles, is at once a division of labor and a design for the performance of work. If a collectivity meets these conditions, so that its members can *act* for it, then it may be said to learn when its members learn for it, carrying out on its behalf a process of inquiry that results in a learning product.

Inquiry is here used in the sense that originates from the work of John Dewey [25]: the intertwining of thought and action that proceeds from doubt to the resolution of doubt. The doubt is construed as the experience of a "problematic situation", triggered by a mismatch between the expected results of action and the results actually achieved. Inquiry becomes organizational when undertaken by individuals who function as members of an organization according to its prevailing roles. The output of an organizational inquiry may take the form of a change in thinking that yields a change in the design of organizational practices. For example, a HCO may experience a poor long-term clinical outcome in the management of a given category of chronic patients. Its investigation of the causes of that finding may result in redesigning home monitoring procedures for an earlier detection of either expected or unexpected adverse effects of a therapy.

Organizational learning is often complicated by the fact that a community shared ontology, or domain model, is often tacit, making it uninspectable and difficult for another community to understand. Supporting such long-term, asynchronous collaboration is particularly important in learning organizations. This requires systems able to support knowledge sharing across workplace communities and across time. However, sharing knowledge is different to simply sharing information: people need support for interpreting each other's perspective and for negotiating a new, shared perspective.

In their seminal work on organization learning, Argyris and Schön [26] describe three different levels of learning. The most basic level is the detection and correction of errors or unjustified clinical actions. They called this type of learning "single loop learning", as it is analogous to maintaining a steady course of a process through use of a feedback system. Single loop learning tends to leave organizational goals and management processes unchanged. Clinical audit or guidelines, for example, in which existing practice outcomes are compared with expected or desired ones, are typical of this type of learning.

More sophisticated learning which changes fundamental assumptions about the organization is possible. This type of learning leads, for example, to a redefining of the organization's goals, values, strategies, procedures, or even structures. Argyris and Schön termed this "double-loop learning" as it calls into question the very nature of the management designed for a process which may be a service for health care professionals or patients. A synthetic representation of both learning systems can be provided by the theory of adaptive control systems, as shown in Fig. 4. The lower part of the diagram represents the single-loop learning while the overall diagram provides a description of double-loop learning.

A control loop implies that the management actions of a care process are decided according to a comparison between expected results (goals) and actual results (outcomes)

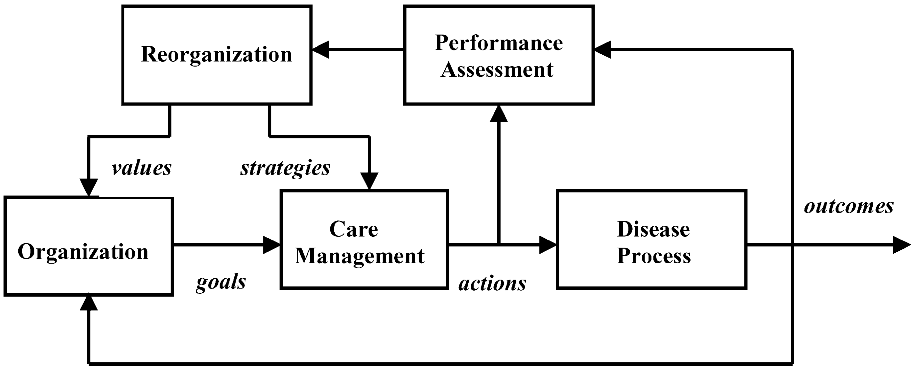

Fig. 4. The single-loop and double-loop learning processes in a HCO viewed as an adaptive control system.

of the process. These can be measured only by defining suitable indicators (values) of effectiveness of care and efficiency in the use of resources: they should allow us to assess whether undertaken actions are bringing the process towards a better performance with respect to the past or other similar processes managed by other HCOs. Besides clinical efficacy indicators, at least two further classes of performance indicators can be defined to assess effectiveness of care: safety of care and quality of life.

The debate on medical errors has been kick started in the USA by a report from the Institute of Medicine [27]. Preventable errors in HCOs result in 44,000–98,000 deaths a year in the USA. The annual toll exceeds the combined deaths and injuries from motor and air crashes, suicides, falls, poisonings, and drownings. The one comparable study from another country, Australia, reported on even a higher rate of errors [28]. The British Medical Journal devoted very recently a whole issue to medical errors — how to recognize, investigate, analyze, and how to change systems to improve patient safety [29]. The error problem can be viewed in two ways: the person approach and the system approach [27]. Each has its model of error causation and each model gives rise to quite different philosophies to error management. Here we are interested more in the second one where errors are seen as consequences rather than causes, having their origins not so much in the perversity of human nature but in socio-organizational factors. Designers of care processes can make them safer by paying attention to three different tasks [30]: designing the system to prevent errors; designing procedures to make errors visible when they occur so that may be intercepted; and designing procedures for mitigating the adverse effects of errors when they are not detected or intercepted. Only learning HCOs can be engaged in pursuing such strategic goals [31].

Another essential class of performance indicators of HCOs are those providing an estimate of the quality of life. This is generally acknowledged as a central concept for measuring the effectiveness of care, but its full application to health care research and clinical practice are still being debated. With an increasing prevalence of chronic diseases and the focus of health care expanding from ‘‘adding years to life’’ to ‘‘adding life to years’’, there is a growing interest in assessments of the quality of life in health care. It is particularly important to investigate the interrelation between the quality of life and the quality of care. However, comprehensive performance evaluations of health care must involve assessments of outcomes and needs. It is only by including both these assessments that the process of care for patients with chronic disease can be improved [32].

When goals and outcomes are well defined and the usually attained performance is satisfactory, the single-loop learning occurs. On the other hand, when performance needs to be improved, a reorganization process starts which needs a continuous monitoring of management actions and consequent outcomes to assess how performance changes according to changes in management strategies and values. This double-loop learning continues until a new management strategy has been identified which increases the overall performance of the process to the desired level. Then, learning switches again to single-loop learning.

Another, usually undeveloped, aspect of learning capacity is the ability of organizations to learn about the context of their learning, when they are able to identify when and how they learn and when and how they do not, and then adapt accordingly. This can be thought as ''learning about learning'' (or meta-learning). It requires a HCO to manage knowledge to support the continuous development of what can be called the organizational learning cycle (OLC). Taking the view of a single HCO, OLC can be represented in the plane of the two knowledge attributes: extent of representation and extent of use. As proposed by Boisot [19] and schematically represented in Fig. 5, it involves the four knowledge conversion processes described by Nonaka and Takeuchi [14]. The externalization process deals with the development of an explicit representation of some useful body of tacit knowledge. Through the next phase, i.e. the combination process, the new evidence is

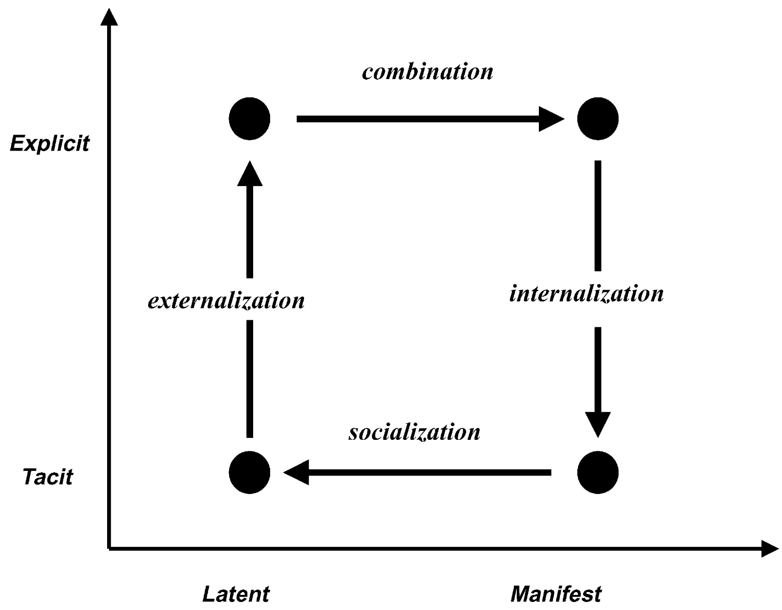

Fig. 5. The meta-learning process in an organization.

combined with established explicit medical knowledge leading to a more complete representation of a care process. This requires the ability to manage medical and organizational ontology and terminology. Then the care process, for example, represented by a computer-based clinical guideline, can be tested and used in a wide variety of contexts and gradually internalized by learners, i.e. health care professionals of the involved HCO. Over time, such learning-by-doing adds a great deal of tacit knowledge to the explicit body of knowledge: it is represented by the results achieved, in terms of clinical outcomes and resource utilization.

The experience gained by applying that guideline can be shared in the socialization phase which can occur within the medical team of a single HCO or across multiple HCOs. Hence, either a refined local adaptation may be derived or the cost-effectiveness of the process may be assessed. Occasionally, however, something akin to a mutation takes place: one or few individuals implement or follow the guideline in idiosyncratic ways and obtain results which are not shared by others. They may appear unexpected but interesting. Thus, the extraction of novel and unique patterns from available data and experience, for example, exploiting tools for data mining, may constitute a source of new knowledge. It reflects a reorganization of data from a manifest yet tacit knowledge, toward a tacit but latent knowledge. In this new form knowledge gets lodged in the heads of few insightful individuals. The new insights may be harbingers of problem areas, of possible threats or opportunities that remain latent in the data and that have to be teased out through a process of creative problem solving. If a given pattern appears promising enough from the results of the data analysis performed by an individual, it invites him to invest time and effort to represent it in some explicit way, thus initiating another round of the OLC.

6. Knowledge representation

Building learning HCOs requires the effective exploitation of new ICT for the management of knowledge, expertise and skills from three different domains: medical, organizational, and technological [33].

By medical domain knowledge we mean any representation of medical work as a set of activities that result from the interaction between patients and heath care professionals. Professionals do their work in an organizational setting: their work depends on the material and financial resources made available through the HCO they work in. There are rules, regulations, and laws, but also unwritten codes and practices that determine the professionals' behavior in an organization. The sociological understanding of these complex practices is essential if we are to introduce ICT into HCOs successfully [34]. They represent the third piece of the puzzle we need to compose to build learning HCOs.

The above mentioned three domains must be integrated with each other to obtain the best possible results in patients' care delivery. Berg writes "that the work of medical personnel is rewritten in the light of the tool and vice versa" [34]. People must communicate and collaborate within an organization, directly or through ICT systems. However, due to different needs and background contexts, there can be varying viewpoints and assumptions regarding what is essentially the same subject matter. The way to address this lack of a *shared understanding* is to reduce or eliminate conceptual and terminological confusion. This requires the creation of a *unifying framework* for the different viewpoints and serves as a basis for communication between people and inter-operability among systems.

Ontology is the term used to refer to the shared understanding which may be used as the unifying framework [35]. An ontology necessarily entails or embodies some sort of world view with respect to a given domain. The world view is often conceived as a set of concepts (e.g. entities, attributes, processes), their definitions and their inter-relationships: this is referred to as a *conceptualization*. Such a conceptualization may be implicit, e.g. existing in someone's head, or explicit, i.e. represented in some formal way and embodied in a piece of software. Shared conceptualizations include conceptual frameworks for modeling domain knowledge; content-specific protocols for communication among inter-operating agents; and agreements about the representation of particular domain theories. Even if the word ontology is sometimes used to refer to the former, the more standard usage and that which we will adopt is that ontology is an explicit account or representation of a conceptualization.

6.1. Medical knowledge

There have been significant efforts to define best clinical practice guidelines to reduce practical variability and to improve the quality of patient care [8]. In many cases, these methods of standardizing care processes have been successful [36]. Yet systematic reviews have shown that the mere existence of these guidelines does not necessarily lead to changes in practice [37]. Certainly, if clinicians are unaware of best practice, they cannot implement them; and if they have not been convinced of their utility, they will not use them. These are goals to be pursued by the medical community. However there are also goals for the AIM community: to increase the power of formal representation approaches of guidelines taking into account complexity, flexibility and uncertainty management needs required by medical decisions and actions and to make them available on line to the right person at the right time at the right cost during his or her daily work [38].

Two main problems for the dissemination and utilization of guidelines still require considerable research efforts: making guidelines site-specific and managing exceptions. National guidelines invariably will require some modification to be useful within a particular clinical setting [18]. How guideline representation will make its adaptation to a specific organization easier and what the performance of modified guidelines within a particular HCO will be are still fundamental research issues. In some instances, guidelines developed to improve patient care and reduce costs may create additional and unanticipated problems when they are used within a HCO [39]. This suggests that there can be organizational problems that may affect the effectiveness and the efficiency of a care process based on a guideline and that cannot be predicted by population-level analysis. To date, however, most guidelines are predominantly focusing on effectiveness issues. While such a focus is necessary to define the effect of a drug, a clinical procedure or a surgical intervention, it is not sufficient to provide the breadth of evidence that guideline users need to derive recommendations for clinical care. The introduction of cost considerations is important because resources for health care are limited and, when considering clinical decisions, the effect on resources may influence recommendations [40]. The Committee on

Clinical Practice Guideline in the USA [8] recommended that every set of guidelines should include information on the cost implications of alternative preventive, diagnostic, and management strategies for the clinical situation in question. However, they then went on to state: "the reality is that this recommendation poses major methodological and practical challenges" as "scientific evidence about benefits and harms is incomplete and accurate cost data are scarce for the great majority of clinical conditions and services". AIM researchers have developed great expertise in building decision models to manage properly uncertain data; they should acquire some additional knowledge from health economics to support HCO managers, when enough data on costs are available, in carrying out methodologically sound cost-effectiveness studies [41].

6.2. Organization modeling

Organizations are diverse and complex, so it may be useful to adopt a simplifying model focusing on their basic elements. An interesting model was proposed by Leavitt [42] and adapted later by Scott [43]: it involves four fundamental elements.

1. *Social structure* refers to the relationships existing among participants in the organization. It can be separated into two components. The first component can be called the *normative structure*: it includes values, norms, and role expectations. Values are the performance indicators employed in defining the goals of the behavior; norms are the generalized rules governing behavior for pursuing goals; and roles are expected behaviors of participants given their position in the social structure. The second component focuses on the actual participants' behavior, rather than on prescriptions for behavior. Thus, it can be called *behavioral structure* and can be represented in terms of activities and interactions. The social structure of an organization varies in the extent to which it is formalized. A formal structure is one in which the social positions and the relationships among organization participants have been explicitly defined independently of the personal characteristics of the participants occupying those positions.
2. *Participants or social actors* are those individuals who contribute to the organization.
3. *Goals* may be defined as conceptions of desired ends, conditions that participants attempt to effect through their work.
4. *Technologies* consist in part of material resources and equipment, but also comprise the technical knowledge and skills of participants.

We can now adopt the following definition of a HCO taking the rational system perspective: HCOs are collectivities oriented towards the pursuit of relatively specific illness prevention and/or management goals and exhibiting relatively highly formalized structures.

They are *purposeful* in the sense that the activities and interactions of participants are coordinated to achieve specific goals. Goals are specific to the extent that they are explicitly defined and provide unambiguous criteria for selecting among alternative activities. The cooperation among participants is *conscious* and *deliberate*; the structure of relations is made explicit and can be *deliberately constructed and reconstructed.* A structure is *formalized* to the extent that the rules governing behavior are precisely and explicitly formulated and to the extent that roles and role relations are prescribed independently of the personal attributes of individuals occupying positions in the structure.

Thus, to model HCOs we need to represent all these elements in some formal way, that is to build an organizational ontology. Which are its basic entities? We should consider that an organization can be represented through a set of constraints on the activities performed by its members. In particular, an organization consists of a set of divisions and subdivisions (recursive definition), a set of organizational members (each is a member of one or more divisions of the organization), a set of roles that members play in the organization, and an organization goal tree that specifies the goals (and their decomposition into subgoals) the members are trying to achieve.

An organization's member may play one or more roles. Each role is defined by the goal set that it must fulfill. Each role is also given enough authority to achieve its goals. Members perform activities in the organizations and consume resources (such as materials, labors, or tools). The constraint set limits the member activities. A member can also work in a team created to perform a special task. She/he has skill requirement and a set of communication links defining the protocol with which she/he communicates with other agents in the organization.

Although some very promising projects developed a generic enterprise ontology [44,45], only very preliminary work has been carried out specifically for HCOs [46].

7. Patient careflow management systems

While clinical guidelines describe the activities of a medical team in a comprehensive manner for the purpose of defining the best practice for patients' management, patient careflows (Cfs) focus on the behavioral aspects of the medical work with regard to a possible support of their execution through advanced ICT. It specializes the concept of workflow in the clinical domain. A workflow is an activity involving the coordinated execution of multiple tasks performed by different agents [47]. These tasks can be manual, or automated, either created specifically for the workflow application being developed, or possibly already existing as legacy programs. The workflow management coalition (WfMC, 1996) defined a basic set of workflow building blocks: activities to execute tasks, transitions between activities, agents performing activities, and workflow relevant data. These building blocks allow the specification of a workflow in terms of complex nets of activities designed to achieve the main goal of the best practice. A *workflow process* is an automated organizational process of task execution management.

Workflow management is the automated coordination, control, and distribution of tasks as required to satisfy a given workflow process. A workflow management system (WfMS) is a set of tools providing support for the necessary service of *workflow design* (which includes its formal representation), *workflow enactment*, and *administration* and *monitoring* of workflow processes. The developer of a workflow application relies on tools for the specification of a workflow process and the data it manipulates. The workflow design is based on a workflow model that is used to represent data and control flow between workflow tasks. The workflow enactment service (including the workflow manager and the workflow runtime system) consists of execution-time components that provide the execution environment. Administrative and monitoring tools are used for managing workflow agents, monitoring the process and the data generated during workflow enactment.

Careflows, as well as workflows, are *case-based*, i.e. every piece of work is executed for a specific patient. One can think of a patient as a *Cf instance*. The goal of workflow management is to handle patients as effectively and efficiently as possible. Patients are handled by executing medical tasks in a specific order. The *Cf process definition* specifies which tasks need to be executed and in what order. A task, which needs to be executed for a specific case, is called a *work item*. Most work items are executed by a *resource*, either human or technological. To facilitate the allocation of work items to resources, resources can be grouped into *classes*. If a resource class is based on the capabilities (i.e. functional requirements) of the HCO members, it is called a *role*. If the classification is based on the structure of the HCO, such a resource class is called an *organizational unit* (e.g. team, laboratory, clinic, department).

An important approach to reengineering a HCO is to analyze its Cf processes and try to find how they can be improved. Typically they are represented by network models designed to simultaneously describe flows and resources in the care process. Multiple levels of abstraction need to be allowed, ranging from executive-level overviews to detailed Cf descriptions. Since many processes appear to be similar or use similar subprocesses, the modeling tool must allow the reuse of models, captured as templates. A graphical interface is also needed by model developers: it must show the flow of activities (tasks) in a process, care objects (inputs to and outputs from activities); and agents. Most typical AI representation formalisms (objects, frames, production rules, semantic networks, etc.) have been used. However, I strongly believe that Petri nets are a well-founded process modeling technique that can be effectively used to represent both clinical guidelines and Cf processes. The classical Petri net was invented by Carl Adam Petri in the sixties [48]. Since then, Petri nets have been used to model and analyze all kinds of processes with applications ranging from protocols, hardware, and embedded systems to flexible manufacturing systems, user interaction and business processes. However, Petri nets could not be used for modeling medical processes until they were extended with color, time, and hierarchy. Some researchers [33,48] convincingly analyzed the several reasons for using Petri nets for workflow modeling. They argued that the most important are the following: formal semantics, expressiveness, and graphical nature. Moreover, Petri nets provide a tool-independent framework for modeling and analyzing processes since they are not based on the software package of a specific vendor.

Petri nets can be also used to represent clinical guidelines. Since it could be very difficult, for non-expert users, to use such a knowledge representation formalism, it is wise to build for them guideline authoring tools with a user-friendly interface which allow first to represent a guideline through a flowchart. Then, for building a Cf model a separate framework can be used to add knowledge about organization structure, actors, roles, and resources. Then, the Cf model can be translated into a standard workflow process definition language. WPDL seems to the best candidate since it is the language recommended by the WfMC [49] for exploiting different existing commercial products for implementing a WfMS. Finally, the Cf model can be translated into a Petri net so allowing the designer of the CfMS to simulate the process to optimize the allocation of resources producing the desired performances. After such analysis, the Cf model can be used to make the CfMS operational.

Many vendors currently offer a WfMSs demonstrating that the software industry recognizes the potential of workflow management tools. However, today's WfMS present some limitations which reduce their applicability to Cf processes. Most severe is the lack of flexibility. That is the possibility to deviate, if required for a specific patient (e.g. in case of unexpected outcomes or emergency situations), from the planned task execution sequence by inserting a new task, dropping a planned task, or even changing the sequence [50–52]. Moreover, the management of temporal constraints, when available, is usually dealing with a simple supervision of deadlines. More advanced features, e.g. the supervision of minimal and maximal time distance, are needed for managing Cf.

The design and development of intra- and inter-organizational Cfs represents another relevant research area to develop for addressing the communication problems within or between HCOs recently analyzed by Coiera [53]. Today's corporations are often required to operate across organizational boundaries. HCO are not exceptions, and are confronted with increasingly dynamic and networked, regional, national, or even international health systems. Phenomena such as innovative telemedicine services extended HCOs and the Internet stimulated cooperation between them.

Therefore, the importance of Cf distributed over a number of HCOs is increasing. Inter-organizational Cf offers HCOs the opportunity to re-shape the health care processes beyond the boundaries of their own organizations. However, inter-organizational Cf is typically subject to conflicting constraints. On the one hand, there is a strong need for coordination to optimize the flow of care in and between the different HCOs. On the other hand, the organizations involved are essentially autonomous and have the freedom to create or modify Cf at any point in time [54].

There is a great need for intelligent tools of communication management within and across HCOs. In order to take into account several users efficiently, current WfMS must evolve towards distributed parallel workflow systems. Multi-agent research seems to be very promising to overcome the limits of traditional WfMS since it is developing new workflow models which parallelize activities and support complex, explicitly represented, negotiation processes among workflow users. This is a way to reduce the burden of synchronous communications among health care professionals increasing the percentage of properly managed asynchronous communications through innovative CfMS. The result will be better communication support for HCO members leading to significant improvements in organizational effectiveness and efficiency. Communication failures are a large contributor to adverse clinical events and outcomes. In a retrospective review of 14,000 in-hospital deaths, communication errors were found to be the lead cause, twice as frequent as errors due to inadequate skills [55]. If we look beyond the raw numbers, the clinical communication space is interruption-driven, has poor communication systems and poor practices [56].

Finally, a CfMS provides the most effective way to support OLC within HCOs. Information about clinical outcomes and resource use is continuously acquired during Cf execution without requiring any extra effort. Analyzing such tacit knowledge facilitates the internalization and socialization process which may lead to the creation of new explicit knowledge which, when it has been shown to be useful, can be combined with already available explicit knowledge. New more effective or efficient Cf models can be developed and the HCO enhances its capabilities through an organizational learning process.

8. Conclusions

The view of an organization as a machine for "information processing" is deeply ingrained in the traditions of management. According to this view, the only useful knowledge is formal and systematic — quantifiable data, codified procedures, universal principles — and the key metrics for measuring the value of new knowledge are similarly hard and quantifiable. But there is another more recent way to think about knowledge and its role in organizations: creating new knowledge is not simply a matter of processing objective information. Rather, it depends on tapping the tacit and highly subjective insights, intuitions, and hunches of individuals and making those available for testing and use by the organization. Moreover, an organization is not a machine but a living organism. Much like an individual, it can have a collective sense of identity and fundamental purpose. To create new knowledge means quite literally to involve everyone and the organization in a continuous process of personal and organizational learning. In a knowledge-creating organization, new knowledge is not only produced by people with special commitments, but it is a way of behaving where everyone is a knowledge producer.

Understanding knowledge transactions within an organization has direct implications for how work processes can be designed and, consequently, roles can be assigned. Some degree of redundancy — the conscious overlapping of information, activities and responsibilities — is important, because it encourages social communication, which is an essential process for transforming tacit into explicit knowledge. Redundancy also spreads new explicit knowledge through the organization so it can be internalized.

Are HCOs substantially different from commercial companies? They are from several viewpoints. However, HCOs and their members are today facing many challenges in health care delivery [57] which resemble those faced by companies in order to compete. These challenges are an increasing demand to improve the quality of care, limited availability of resources, the growing complexities of biomedical research, and the astonishing advances in ICT. Traditional HCO management strategies are giving way to innovative management of medical knowledge to build socio-organizational contexts where patients, physicians and other health care professionals are able not only to exploit explicit knowledge sources during their activities, but also to convert tacit into explicit knowledge. This is the only way to quickly embody useful personal knowledge coming from research results and clinical practice. Any decision support system that AIM researchers may develop is of limited utility if it does not evolve under the pressure of the results of its testing and using. Moreover, it needs to be integrated into the Cf process.

Improving clinical effectiveness is showing that success in implementing evidence-based practice is achieved only when there are real local partnerships between clinicians and managers [58]. The challenge is not to turn clinicians into managers but to recognize that some aspects of the task are the direct responsibility of managers. In fact, clarity about responsibilities is a prerequisite for success. Clinicians need to review local practice against available evidence and help determine priorities for change, a subsequent task to be handled jointly by clinicians and managers. Managers can help ensure adequate organizational skills and resources. This represents another strategic goal for the AIM community: the development of greater expertise in analyzing social processes in HCOs and designing new tools for reengineering them by exploiting advanced ICT.

Thus, AIM researchers should work to develop tools for building what Etienne Wenger called "communities of practice" [59]. This notion was further extended by Seely Brown and Duguid [60] who have taken the topic of "the social life of information". They show how a better understanding of the contribution that communities, organizations, and institutions make to learning and knowledge creation can lead to the richest possible use of technology in our daily life and work. For a very long time we have oriented our research efforts only towards developing new methods for manipulating medical information and knowledge. So we missed the real problem: creating and managing knowledge are defining features of organizations. We must be able to analyze how an organization is structured as an information and knowledge processing organization and how the underlying practices of the people that work there fit with those processes. Really good organizations work by balancing these two things: process and practice, or what can be otherwise called the *structure* and the *spontaneity* of an organization. Each one of those is always threatening to overcome the other. The balancing act is really difficult, but it is the most relevant goal to pursue. An effective management of medical knowledge to innovate services for patients requires organizations properly structured. To do this, we must take account much more of what people *actually do* than what, as designers of new software tools, we *would like* people to do. Rather than think of people as resistant to new ideas, we need to look forward to the challenge of leading those people, willingly, onto interesting new ways of working together exploiting advanced ICT.

Such a socio-organizational view of health care represents the basis for managing HCOs as learning organizations. Medical informatics is the discipline which provides the methodologies for designing, developing, and evaluating the basic information and communication infrastructure, while AIM makes available innovative methodologies for organizational knowledge management. They must cooperate to increase effectiveness and efficiency of HCOs in the interest of the whole society. To achieve such a strategic goal, the AIM community should activate new multidisciplinary research projects, based on mutual respect and willingness to integrate into its culture other disciplines, such as organization management, psychology, sociology, and anthropology in order to design and develop knowledge management tools which integrate smoothly into a computer-supported collaborative work framework.

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References

[1] Fox J, Rahmanzadeh A. Disseminating medical knowledge: the PROforma approach. Artif Intell Med 1998;14:157–81.

[2] Boxwala AA, Greenes RA, Deibel SR. Architecture for a multipurpose guideline execution engine. In:

Lorenzi NM, editor. Proceedings of the AMIA '99 Annual Symposium. Philadelphia, PA: Hanley & Belfus, 1999, pp. 701–5.
[3] Sugden B, Purves IN, Booth N, Sowerby N. The PRODIGY project — the interactive development of the release one model. In: Lorenzi NM, editor. Proceedings of the AMIA '99 Annual Symposium. Philadelphia, PA: Hanley & Belfus, 1999, pp. 359–63.
[4] Tu SW, Musen MA. A flexible approach to guideline modeling. In: Lorenzi NM, editor. Proceedings of the AMIA '99 Annual Symposium. Philadelphia, PA: Hanley & Belfus, 1999, pp. 420–4.
[5] Haines A, Jones R. Implementing findings of research. Br Med J 2000;308:1488–92.
[6] Glanville J, Haines M, Auston I. Finding information on clinical effectiveness. Br Med J 1998;317:200–3.
[7] Quaglini S, Dazzi L, Gatti L, Stefanelli M, Fassino C, Tondini C. Supporting tools for guideline development and dissemination. Artif Intell Med 2000;14:119–37.
[8] Field MJ, Lohr KN. Clinical practice guidelines: direction for a new program. Washington, DC: National Academic Press, 1990.
[9] Feder G, Eccles M, Grol R, Griffiths C, Grimshaw J. Using clinical guidelines. Br Med J 1999;318:728–30.
[10] Brooking A. Intellectual capital. London, UK: International Thomson Business Press, 1996.
[11] Choo CW. The knowing organization. New York, NY: Oxford University Press, 1998.
[12] Polanyi M. The tacit dimension. London, UK: Routledge & Kegan Paul, 1966.
[13] Thirup P, Mikkelsen P. Tacit knowledge — an epistemological framework and implications in doctors information needs. In: Hasman A, Blobel B, Dudek J, Engelbrecht R, Gell G, Prokosch HU, editors. Proceedings of MIE 2000 and GMDS 2000. Amsterdam, NL: IOS Press, 2000.
[14] Nonaka I, Takeuchi H. The knowledge-creating company. Oxford, UK: Oxford University Press, 1995.
[15] Schreiber ATh, Akkermans JM, de Hoog R, Shadbolt NR, Van de Velde W, Wielinga BJ. Knowledge engineering and management. The common KADS methodology. Cambridge, MA: MIT Press, 2000.
[16] Nelson R, Winter S. An evolutionary theory of economic change. Cambridge, MA: Harward University Press, 2000.
[17] Haynes B, Haines A. Barriers and bridges to evidence based clinical practice. Br Med J 2000;317:273–6.
[18] Fridsma DB, Gennari J, Musen M. Making protocols site-specific. In: Cimino J, editor. Philadelphia, PA: Hanley & Belfus, 1996, pp. 597–601.
[19] Boisot MH. Information space: a framework for learning in organizations, institutions and culture. London, UK: Routledge, 1995.
[20] Cowan R, David PA, Foray D. The explicit economics of knowledge codification and tacitness. Ind Corporate Change 2000;9:211–53.
[21] Simon HA. Models of man: social and rational. New York, NY: Wiley, 1957.
[22] Mintzberger H, Raisinghani D, Théorêt A. The structure of unstructured decision processes. Administrative Sci Q 1976;21:246–75.
[23] Boland RJ, Tenkasi RV. Perspective making and perspective taking in communities of knowing. Organization Sci 1995;6:350–72.
[24] Barnard C. The functions of the executive. Cambridge, MA: Harvard University Press, 1938.
[25] Dewey J. Logic: the theory of inquiry. New York, NY: Holt, Rinehart & Winston, 1938.
[26] Argyris C, Schön D. Organizational learning II. London, UK: Addison-Wesley, 1996.
[27] Reason J. Human error: models and management. Br Med J 2000;320:768–70.
[28] Weingart SN, Wilson RM, Gibberd RW, Harrison B. Epidemiology of medical error. Br Med J 2000;320:774–7.
[29] Barley V, Neale G, Burns-Cox C, Savage P, Machin S, El Sobky A, Savage A, Sheikh A, Hurwitz B, Connolly CK, Jonsson PM, Tomson G, Raf L, McCune K, Law R, Goss RM, Estrada CA, Carter J, Brooks C, Jobe AC, Aldridge J, Freeland P, Ashcroft B, Eistein M, Boreham N, Shirley PJ, Strunin L, Morgan M, Cartwright P, Coffey RP. Reducing error improving safety. Br Med J 2000;321:505–14.
[30] Nolan TW. System changes to improve patient safety. Br Med J 2000;320:771–3.
[31] Department of Health. An Organisation with a Memory. Cambridge, MA: The Stationary Office, London, 2000, http://www.dch.gov.uk/orgmemreport/index.htm.
[32] van den Bos GAM, Triemstra AHM. Quality of life as an instrument for need assessment and outcome assessment of health care in chronic patients. Quality Health Care 1999;8:247–52.
[33] van der Aalst WMP. Three good reasons for using a Petri-net-based workflow management system. In:

Wakayama T, Kannapan T, Khoong CM, Navathe S, Yates J, editors. Information and process integration in enterprises: rethinking documents. Boston, MA: Kluwer Academic Publishers, 1998, pp. 161–82.
[34] Berg M. Rationalizing medical work-decision support techniques and medical practices. Cambridge, MA: MIT Press, 1997.
[35] Uschold M. Knowledge level modeling: concepts and terminology. Knowledge Eng Rev 2000;13:5–30.
[36] Ellrodt AG, Conner L, Ridinger M. Measuring and improving physician compliance with clinical practice guidelines: a controlled interventional trial. Ann Internal Med 1995;122:277–82.
[37] Eisenberg PJ, Greco JM. Changing physicians' practices. New Engl J Med 1993;321:1306–11.
[38] Fridsma DB, Thomsen J. Representing medical protocols for organization simulation: an information processing approach. Comp Math Organization Theory 1998;4:71–95.
[39] Gensensway D. Putting guidelines to work — lessons from the real world. ACP Observer 1995;15:15–27.
[40] Eccles M, Mason J, Freemantle N. Developing valid cost effectiveness guidelines: a methodological report from the north of England evidence based guideline development project. Quality Health Care 2000;9:127–32.
[41] Quaglini S, Dazzi L, Stefanelli M, Barosi G, Marchetti M. Decision support systems in health economics. Topics Health Inf Manage 1999;20:16–30.
[42] Leavitt H. Applied organizational change in industry: structural, technological and humanistic approaches. In: March J, editor. Handbook of organizations. Chicago, MI: Rand McNally, 1965, pp. 1144–70.
[43] Scott WR. Organizations: rational, natural and open systems. Englewood Cliffs, NJ: Prentice-Hall, 1992.
[44] Fox MS, Gruninger M. Enterprise modeling. AI Magazine 2000;1998:109–21.
[45] Uschold M, King M, Moralee S, Zorgios Y. The enterprise ontology. Knowledge Eng Rev 1998;13:31–89.
[46] Falasconi S, Dazzi L, Lanzola G, Quaglini S, Saracco R, Stefanelli M. Towards cooperative patient management through organizational and medical ontologies. Methods Inf Med 1998;37:564–75.
[47] Krishnakumar N, Sheth A. Managing heterogeneous multi-system tasks to support enterprise-wide operations. Distributed Parallel Databases 1995;3:155–86.
[48] Jensen K. Coloured Petri nets. Basic concepts, analysis methods and practical use. Berlin: Springer, 1996.
[49] Lawrence P. Workflow handbook. Chichester, UK: Wiley, 1997.
[50] Casati F, Ceri S, Paraboschi S, Pozzi S. Specification and implementation of exceptions in workflow management systems. ACM Transactions on Database Systems, 1999.
[51] Muller R, Rahm E. Rule-based modification of workflows in a medical domain. In: Buchmann AP, editor. BTW99. Berlin: Springer, 1999, pp. 429–48.
[52] Dadam P, Reichert M. Towards a new dimension in clinical information processing. In: Hasman A, Blobel B, Dudek J, Engelbrecht R, Gell G, Prokosch HU, editors. Proceedings of MIE 2000 and GMDS 2000. Amsterdam, NL: IOS Press, 2000, pp. 295–301.
[53] Coiera E. When communication is better than computation. J Am Med Inf Assoc 2000;7:277–86.
[54] van der Aalst WMP. Modeling and analyzing inter-organisational workflows. In: Proceedings of the 1998 International Conference on Application of Concurrency to System Design (CSD'98). Fukushima, Japan: IEEE Computer Society Press, 1998, pp. 262–72.
[55] Wilson RM, Runciman WB, Gibberd RW, Harrison BT, Newby L, Hamilton JD. The quality in Australian health care study. Med J Australia 1995;163:458–71.
[56] Coiera E, Tombs V. Communications behaviour in hospital settings: an observational study. Br Med J 1998;316:673–6.
[57] Greenes RA, Lorenzi NM. Audacious goals for health and biomedical informatics in the new millennium. J Am Med Inf Assoc 1998;5:395–400.
[58] Dunning M, Lugon M, MacDonald J. Is clinical effectiveness a management issue? Br Med J 1998;316:243–4.
[59] Wenger E. Communities of practice. New York, NY: Cambridge University Press, 1998.
[60] Seely Brown J, Duguid P. The social life of information. Boston, MA: Harvard Business School Press, 2000.